CDF Note 9202

Search for the Flavor Changing Neutral Current Decay $t \to Zq$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV with 1.9 fb^{-1} of CDF-II Data

The CDF Collaboration
URL `http://www-cdf.fnal.gov`

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We present a search for the flavor changing neutral current decay of the top quark $t \to Zq$ with CDF Run II data corresponding to $1.9\,\mathrm{fb}^{-1}$ of integrated luminosity. The decay $t \to Zq$ is extremely rare in the standard model and a signal at the Tevatron would be an indication of new physics. Using $Z+ \geq 4$ jet candidate events both with and without a loose secondary vertex b-tag, we discriminate signal from background by exploring kinematic constraints present in FCNC events. We construct a mass χ^2 variable and fit templates to the data, taking into account shape systematic uncertainties of the χ^2 distribution. We find a χ^2 distribution consistent with the background expectations and employ a Feldman-Cousins limit technique to set a 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ of 3.7%. The expected limit in the absence of a signal is 5.0%. This is currently the world's best limit on $\mathcal{B}(t \to Zq)$ and improves the best published limit, which was inferred indirectly from the non-observation of $e^+e^- \to tq$ at LEP, by more than a factor of 3.5.

Preliminary Result for Winter Conferences 2008

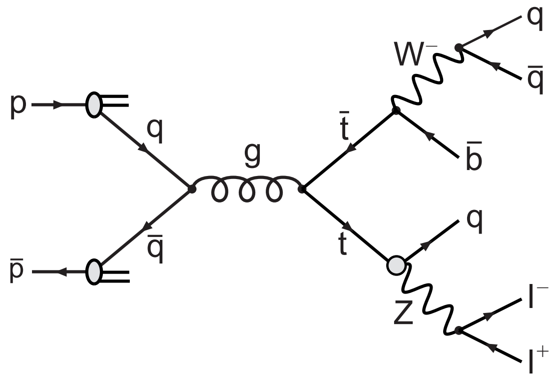


FIG. 1: Feynman diagram of $t\bar{t}$ production and a subsequent FCNC decay of one top quark into a Z boson and u or c quark, while the W boson from $t \to Wb$ decays hadronically. This results in a final state with a Z and four jets.

I. INTRODUCTION

A. Theoretical Background and Previous Results

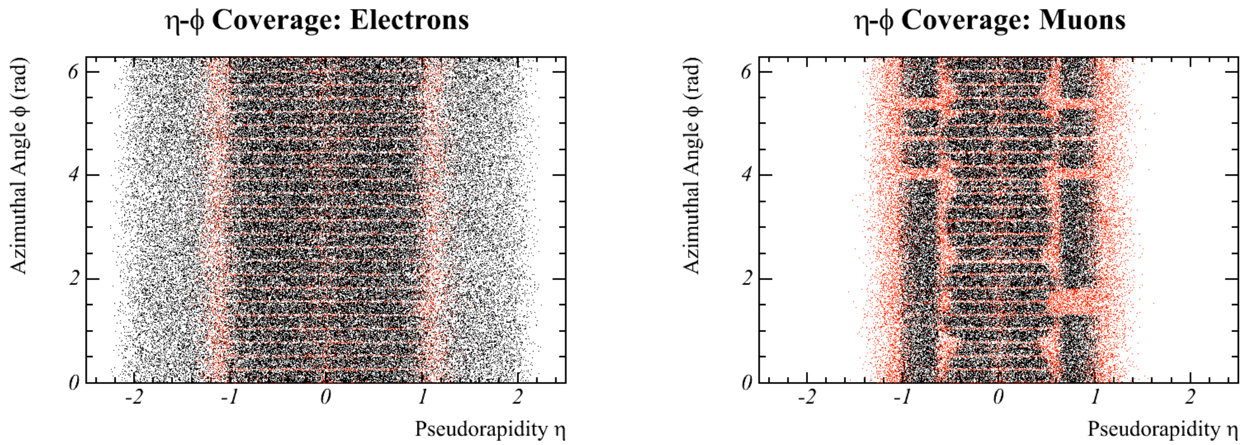
In the standard model of particle physics (SM), flavor changing neutral current (FCNC) decays are highly suppressed. They do not occur at tree level, and are only allowed at the level of quantum loop corrections at very small branching fractions. A search for the top quark FCNC decay $t \to Zq$ at the Tevatron was first proposed by H. Fritzsch in 1989 [1]. The branching fraction for the decay $t \to Zq$ is predicted to be $\mathcal{O}(10^{-14})$, far below the experimental sensitivity of the Tevatron or even the Large Hadron Collider (LHC). As summarized in an article by J.A. Aguilar-Saavedra [2], there exist new physics models that predict much higher branching fractions, up to $\mathcal{O}(10^{-4})$. Any detection of top's FCNC decay at the Tevatron would be an indication of new physics.

Previous searches for the FCNC $t \to Zq$ have been performed in CDF Run I, by the LEP experiments, and recently in CDF Run II. The Run I analysis yielded an upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ of 33% at 95% C.L. [3]. The current best published 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ is 13.7%, inferred from the L3 experiment's non-observation of $e^+e^- \to tq$ [4]. We have presented preliminary results of the first Tevatron Run II top FCNC search for the summer conferences 2007. Based on 1.1 fb^{-1} of data, we derived a limit of $\mathcal{B}(t \to Zq) < 10.4\%$ at 95% C.L. [5].

B. Analysis Method

We search for the FCNC decay $t \to Zq$ by examining $t\bar{t}$ events in which either top quark decays via an FCNC to a Z boson and a quark (u or c), and the other top quark undergoes the regular SM decay to a W boson and a b quark. We examine the decay channel in which the Z subsequently decays to a pair of charged leptons (e^+e^- or $\mu^+\mu^-$) and the W decays to two quarks. The final experimental signature of the FCNC comprises a reconstructed Z and four or more jets, one of which is a b-jet that can be identified by a b-tagging algorithm. The signature does not include any neutrinos in the final state, and we are therefore able to fully reconstruct the event. See Fig. 1 for an illustration.

The event selection used in this top FCNC search has been optimized for the summer 2007 analysis [5] and remains unchanged in this analysis. We construct a mass χ^2 variable that combines the kinematic constraints present in top FCNC decays to separate signal from background. We build templates for the signal expected from the top FCNC decay $t \to Zq$ and for all significant SM background contributions. We take the signal acceptances and trigger efficiencies from a Monte Carlo simulation with appropriate corrections for the simulation's deficiencies applied. We normalize the event yield to the top pair production in the lepton+jets channel. We fit the mass χ^2 templates to the data and use a Feldman-Cousins construction with systematic uncertainties to derive an upper limit on the branching fraction $\mathcal{B}(t \to Zq)$.



(a) (b)

FIG. 2: Improved lepton η–ϕ coverage using track leptons for (a) electrons and (b) muons. The black points show the coverage with tight leptons only, the red points show the additional coverage gained by using track leptons.

TABLE I: Event selection criteria.

Kinematic Variable	**Optimized Cut**
Transverse Mass	≥ 200 GeV
Leading Jet E_T	≥ 40 GeV
Second Jet E_T	≥ 30 GeV
Third Jet E_T	≥ 20 GeV
Fourth Jet E_T	≥ 15 GeV

II. ANALYSIS OVERVIEW

A. Data Sample and Event Selection

For this analysis, we use data collected with the CDF II detector between March 2002 and May 2007, which corresponds to an integrated luminosity of 1.9 fb^{-1}. We require that the data from the silicon detector, from the electromagnetic calorimeter, and from muon chambers are marked "good" in the data quality assessment. The data for this analysis was collected with inclusive lepton triggers that require transverse energies of $E_T > 18$ GeV for electrons and transverse momenta of $p_T > 18$ GeV$/c$ for muons.

For the base event selection we reconstruct a Z and four or more jets. The Z selection requires exactly one lepton pair of the same flavor and opposite charge. One of the leptons must pass tight selection and lepton identification criteria, the other lepton can be formed from an isolated track in the silicon detector and the drift chamber. This results in twice the acceptance compared to using tight leptons only, see Fig. 2. The invariant mass of the lepton pair must fall into the range between 76 GeV$/c^2$ and 106 GeV$/c^2$. We correct the energies of reconstructed jets to the parton level and initially require the jets to have corrected $E_T \geq 15$ GeV and to fall into the pseudorapidity range of $|\eta| < 2.4$ [6].

We have optimized the event selection for the previous version of this analysis, a blind counting experiment, and keep the selection for the current version (removing the cut on the mass χ^2 present in the counting experiment and performing a fit to mass χ^2 templates instead). The optimized event selection includes additional cuts, on the transverse mass of the events, and on the transverse energies of the four leading jets, as listed in Table I.

Our strongest discriminant to distinguish signal from background is a mass χ^2 variable. In a signal event, there is one decay of the type $t \to Wb$. Two jets in the event form a W, which in turn forms a top quark together with a third jet. There is also one decay of the type $t \to Zq$, in which the Z has to be paired with the fourth jet to form the

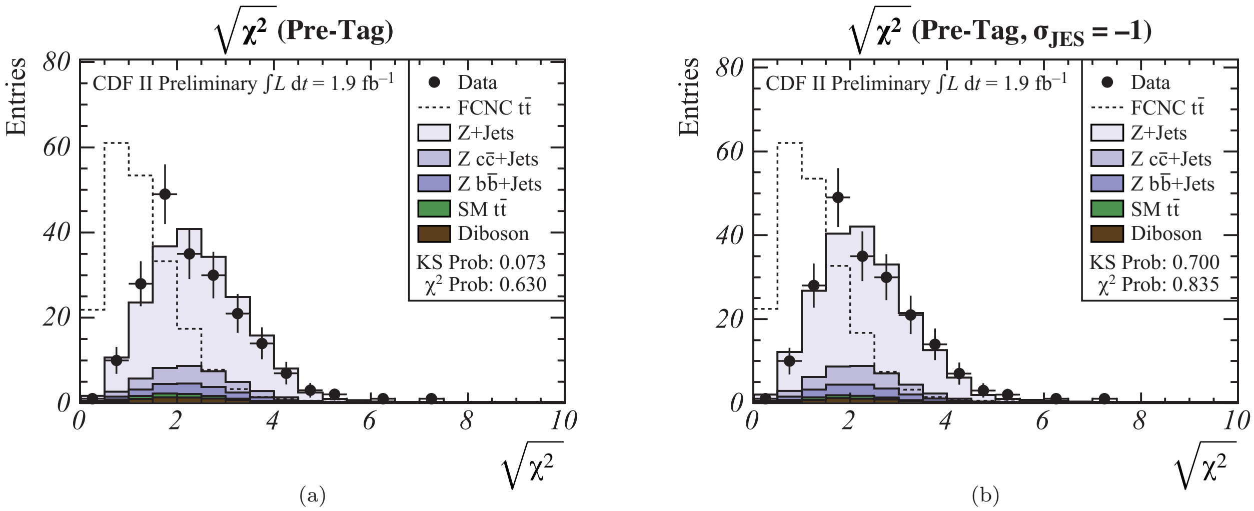


FIG. 3: Data-MC comparison of the mass χ^2 distribution for base selection ("pre-tag") (a) for nominal jet energy scale and (b) for a -1σ jet energy scale shift. The standard model (SM) top and diboson backgrounds are fixed to their absolute predictions, and the Z+jets backgrounds are scaled such that the total background integral matches the number of observed data events. The dashed line shows the shape of the expected FCNC signal, normalized to the number of observed data events.

second top quark. The mass χ^2 is defined as

$$\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,\mathrm{rec}}}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2, \tag{1}$$

where we assume a top mass of 175 GeV$/c^2$ and the mass resolutions $\sigma_{W,\mathrm{rec}} = 15$ GeV, $\sigma_{t\to Wb} = 24$ GeV, and $\sigma_{t\to Zq} = 21$ GeV, as measured in the Monte Carlo simulation. We evaluate χ^2 for all permutations of the leading four jets in the event and select the permutation with the lowest χ^2. In addition, we cut on the transverse mass of the four leading jets and the Z,

$$m_T = \sqrt{\left(\sum E_T\right)^2 - \left(\sum \vec{p}_T\right)^2}, \tag{2}$$

to discriminate top decays, which tend to be central, from the more forward decaying Z+jets events.

B. Template Fit

The key element of this analysis is a template fit to the measured mass χ^2 distribution. The template fit analysis improves upon the sensitivity of the summer 2007 analysis because it explores the full χ^2 shape information to measure $\mathcal{B}(t \to Zq)$. The fit also reduces the dependence on absolute predictions of background contributions by making the background normalization a free fit parameter. On the other hand, the template fit requires good control of the template shapes. We found that the largest uncertainties in the mass χ^2 shape are induced by uncertainties in the choice of the jet energy scale (JES), as illustrated in Fig. 3.

The influence of all other shape uncertainties is much smaller than the JES shape uncertainty; therefore we take the JES shift as representative for all sources of shape uncertainties. We have introduced the "horizontal template morphing" technique [7] to the template fit (see Fig. 4 for an illustration), so that the fit treats shifts in the JES as a continuous fit parameter by interpolating between templates at discrete values of the JES shift.

To increase the sensitivity of the template fit, we split the data sample into two signal regions. The b-tagged signal region requires one or more b-tags of the "loose" flavor of the standard CDF secondary vertex b-tagging algorithm (SECVTX), and the anti-b-tagged signal region contains events with exactly zero b-tags. In order to control uncertainties in the background shape, we also introduce a control region with large background acceptance and small signal contamination. The control region contains all events that pass the base selection (reconstructed Z and four or more jets) but fail at least one of the selection criteria of Table I. Additionally we use the fitted number of events in

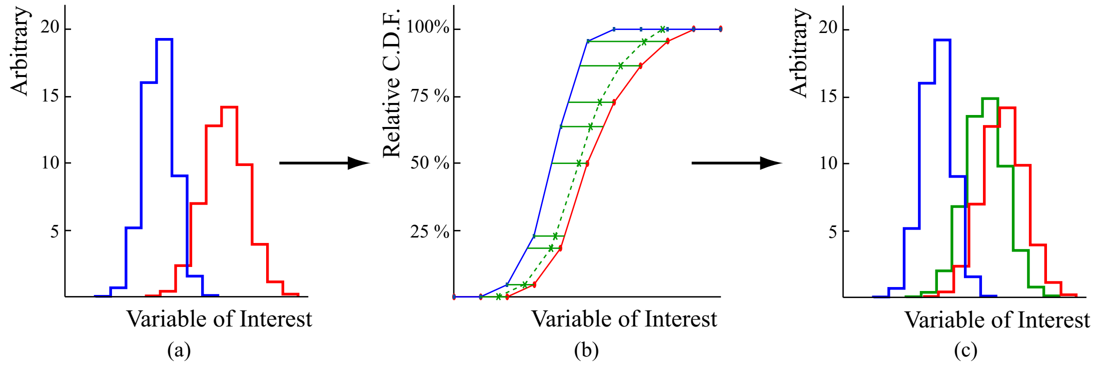


FIG. 4: Illustration of horizontal template morphing. A 75% morphed histogram is obtained by (a) constructing cumulative distribution functions (C.D.F.s) of the two source histograms, (b) constructing a new C.D.F. as the 75% interpolation between the C.D.F.s of the source histograms, and (c) taking the derivative of the resulting C.D.F.

TABLE II: Summary of the small background contributions to the search for the FCNC decay $t \to Zq$. Given are the expected numbers of background events in 1.9 fb^{-1}, and the cross sections for each of the processes.

Source	**Cross Section (pb)**	**Events Tagged**	**Events Anti-Tagged**	**Events Control**
Standard Model $t\bar{t}$	8.8±1.1	1.7±0.2	0.7±0.1	1.8±0.2
Diboson WZ	3.96±0.06	0.2±0.1	1.4±0.1	2.1±0.1
Diboson ZZ	3.40±0.25	0.3±0.1	1.1±0.1	1.8±0.1

the control region to apply a loose (20%) constraint on the number of events expected in the two signal regions, where the uncertainty is derived from systematic variations of internal parameters of the ALPGEN Monte Carlo generation, as detailed in Section III B. In summary, the following five parameters are used in the template fit:

- branching fraction $\mathcal{B}(t \to Zq)$,
- number of Z+jets events in the control region,
- shift in the ratio of Z+jets events in the signal regions vs. the control region (Gaussian constraint, 20%),
- tagging fraction, i.e. fraction of signal events in the b-tagged signal region, and
- shift in jet energy scale.

C. Background Processes

There are several physics processes that have signatures consistent with our event selection. The dominant background contribution for this analysis comes from Z bosons produced in association with jets (Z+jets). The template fit technique relies on the shape of the mass χ^2 distribution for Z+jets events but not on absolute predictions of the amount of Z+jets events. This is in contrast to the blind counting experiment performed in the analysis presented in summer 2007, which required absolute predictions for all background contributions.

A much smaller background contribution comes from SM top pair decays, $t\bar{t} \to WbWb$, in which the invariant mass of two leptons in the dilepton decay mode or a lepton and a jet misidentified as a lepton in the lepton+jets decay mode fall within the Z mass window. A contribution similar in size comes from diboson events which contain a real Z boson (WZ and ZZ). The SM top and diboson backgrounds are estimated using Monte Carlo simulations. We found background contributions from WW diboson and W+jets production negligible; these processes do not contain a real Z in the final state. Table II shows the expected number of events in the two signal regions and the control region in 1.9 fb^{-1} of data.

D. Acceptance Calculation

The acceptance calculation for this analysis is based on detailed MC simulations. All FCNC signal samples have been created with the Pythia event generator, version 6.216 [8], assuming a top quark mass of 175 GeV/c^2. We re-weight the samples such that the helicity of the Z boson from the $t \to Zq$ decay is 65% longitudinal and 35% left-handed, where the magnitude of the longitudinal component has been chosen such that it matches the prediction of an SM-like Higgs mechanism. We assign a systematic uncertainty of 3.5% due to this unknown aspect of the tZc interaction, corresponding to half the total possible deviation in acceptance.

The event yield expected from the FCNC decay $t \to Zq$ is normalized to the measured $t\bar{t}$ cross section in the lepton+jets channel. The acceptance calculation accounts for the overlap between the two channels and all contributions to the total FCNC event yield: The $t\bar{t}$ cross section is re-interpreted assuming the presence of FCNC decays. The acceptance for the FCNC decay is composed of events in which one of the top quarks decays via the FCNC and events in which both tops decay via the FCNC. These considerations result in an acceptance formula in which the acceptance depends on the variable to be measured, in our case the branching fraction $\mathcal{B}(t \to Zq)$. This dependence is accounted for in the template fit. The number of expected FCNC signal events $N_{\rm signal}$ is given by the probabilities $\mathcal{P}$ for one or both of the top quarks decaying via an FCNC, the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$, and the integrated luminosity $\int \mathcal{L}\,\mathrm{d}t$:

$$
\begin{aligned}
N_{\rm signal} &= \{\mathcal{P}(t\bar{t} \to WbZq) \cdot \mathcal{A}_{WZ} + \mathcal{P}(t\bar{t} \to ZqZq) \cdot \mathcal{A}_{ZZ}\} \cdot \sigma_{t\bar{t}} \cdot \int \mathcal{L}\,\mathrm{d}t \\
&= \mathcal{B}_Z \cdot (N_{\rm LJ} - B_{\rm LJ}) \cdot \frac{\mathcal{A}_{WZ}}{\mathcal{A}_{WW,\rm LJ}} \cdot \frac{2 \cdot (1 - \mathcal{B}_Z) + \mathcal{R}_{ZZ/WZ} \cdot \mathcal{B}_Z}{(1-\mathcal{B}_{\rm z})^2 + 2 \cdot \mathcal{B}_{\rm z} \cdot (1 - \mathcal{B}_{\rm z}) \cdot \mathcal{R}_{WZ/WW,\rm LJ} + \mathcal{B}_{\rm z}^2 \cdot \mathcal{R}_{ZZ/WW,\rm LJ}},
\end{aligned} \tag{3}
$$

where

$$
\begin{aligned}
\mathcal{B}_Z &\equiv \mathcal{B}(t \to Zq) = 1 - \mathcal{B}(t \to Wb), \\
N_{\rm LJ} &\equiv \text{Lepton+Jets Event Yield}, \\
B_{\rm LJ} &\equiv \text{Lepton+Jets Background}, \\
\mathcal{A}_{WZ} &\equiv \text{FCNC Acceptance for } t\bar{t} \to Zq\,Wb, \\
\mathcal{A}_{ZZ} &\equiv \text{FCNC Acceptance for } t\bar{t} \to Zq\,Zq, \\
\mathcal{A}_{WW,\rm LJ} &\equiv \text{Lepton+Jets Acceptance for SM } t\bar{t} \to Wb\,Wb, \\
\mathcal{A}_{WZ,\rm LJ} &\equiv \text{Lepton+Jets Acceptance for } t\bar{t} \to Zq\,Wb, \\
\mathcal{A}_{ZZ,\rm LJ} &\equiv \text{Lepton+Jets Acceptance for } t\bar{t} \to Zq\,Zq, \\
\mathcal{R}_{ZZ/WZ} &\equiv \mathcal{A}_{ZZ}/\mathcal{A}_{WZ}, \\
\mathcal{R}_{WZ/WW,\rm LJ} &\equiv \mathcal{A}_{WZ,\rm LJ}/\mathcal{A}_{WW,\rm LJ}, \\
\mathcal{R}_{ZZ/WW,\rm LJ} &\equiv \mathcal{A}_{ZZ,\rm LJ}/\mathcal{A}_{WW,\rm LJ}.
\end{aligned}
$$

We found that the best choice for the normalization channel is the $t\bar{t}$ production cross section measurement that requires two or more loose SECVTX b-tags. The event selection of the double b-tag analysis is similar enough to the FCNC selection for parts of the systematics to cancel. At the same time, the sensitivity of the analysis is enhanced because the lepton+jets acceptance of the FCNC signal, i.e. the terms $\mathcal{R}_{WZ/WW,\rm LJ}$ and $\mathcal{R}_{ZZ/WW,\rm LJ}$ in the denominator of the acceptance correction of Eq. (3), is reduced. Note that the integrated luminosity cancels in the above equation.

E. Limit Calculation

To derive a limit on the branching fraction $\mathcal{B}(t \to Zq)$ we employ a Feldman-Cousins method including systematic uncertainties. The Feldman-Cousins method is ideal for analyses with very small signal expectations like this top FCNC search in that it ensures a physical limit even for unphysical measured values, in our case negative values of $\mathcal{B}(t \to Zq)$. We build the Feldman-Cousins construction for this analysis based on pseudo-experiments for true values of $\mathcal{B}(t \to Zq)$ between 0% and 16%. A single pseudo-experiment consists of (Poisson) random mass χ^2 distributions in the two signal regions and the control region, generated from the signal and background templates and taking into account all known systematic effects and their correlations among the signal and control regions. We extract a measured value of $\mathcal{B}(t \to Zq)$ by applying the template fit to the pseudo-experiment. From the Feldman-Cousins construction, we derive an expected limit in the absence of signal of 5.0%. Fig. 5 shows the resulting Feldman-Cousins band and and the expected limit.

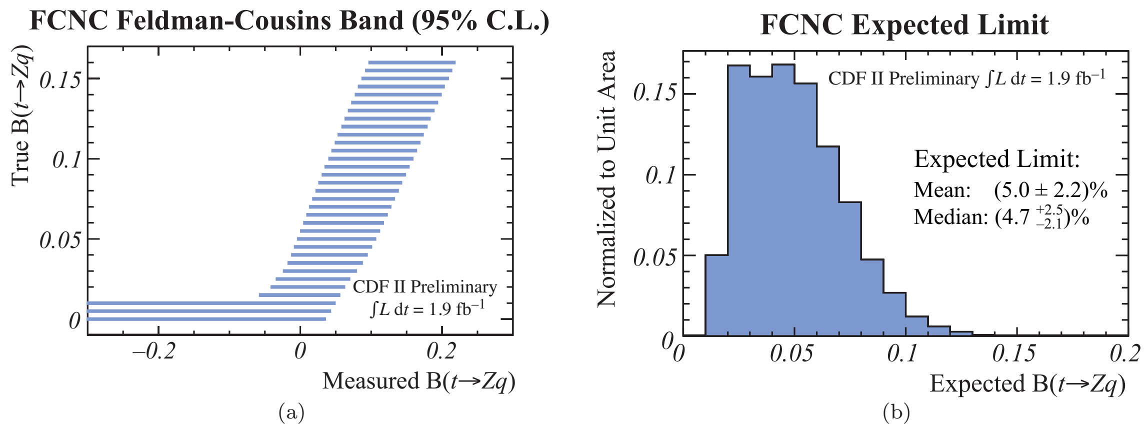


FIG. 5: (a) The 95% C.L. Feldman-Cousins band for the top FCNC search. (b) Expected 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq)$.

III. SYSTEMATIC UNCERTAINTIES

The search for the top FCNC decay $t \to Zq$ is based on a template fit to the mass χ^2 distribution. As a consequence, we take into account systematic uncertainties in both the event rate and the mass χ^2 shape, for the signal acceptance as well as for the expected background.

A. Rate Uncertainties

1. *Signal Acceptance*

As the event yield is normalized to the measured lepton+jets top production cross section, we attribute systematic uncertainties to the ratio of the FCNC acceptance to the acceptance used in the cross section analysis, $\mathcal{A}_{WZ}/\mathcal{A}_{WW,\mathrm{LJ}}$, distinguishing between correlated and anti-correlated uncertainties. Uncertainties which we label as correlated are those which shift the number of events in both the anti-tagged and the tagged signal regions in the same direction.

We attribute correlated systematic uncertainties to Monte Carlo corrections factors (lepton scale factors for lepton identification efficiencies and separate trigger efficiencies), and estimations on initial state radiation (ISR) and final state radiation (FSR) from the event. Since our signal Monte Carlo sample is generated flat in $\cos(\theta^*)$, the angle between the top boost and the positive lepton in the Z rest frame, we chose to re-weight it to the handedness expected from a standard model like Higgs mechanism: 65% longitudinal and 35% left-handed. We apply a systematic uncertainty on this helicity re-weighting of the signal FCNC Monte Carlo sample. We also include a correlated systematic uncertainty on the parton distribution functions. The jet energy scale uncertainty is not considered here as the shift in the jet energy scale is a free parameter in the template fit. The measurement is normalized to the lepton+jets top production cross section, so that luminosity uncertainties cancel in the ratio.

Systematic uncertainties that are anti-correlated shift the number of events in the anti-tagged and tagged signal regions in opposite directions. We attribute an anti-correlated systematic uncertainties on the b-tagging scale factors and the mistag parameterization applied to the Monte Carlo simulation. We also include an anti-correlated systematic uncertainty for the difference in event tagging rate between $t\bar{t} \to ZuWb$ and $t\bar{t} \to ZcWb$ decays. Table III contains a summary of all systematic rate uncertainties.

2. *Background Rate*

The number of Z+jets events in the control region is a free parameter in the template fit; therefore uncertainties of the background rate affect only the smaller backgrounds from standard model top pair and diboson decays. The background rate uncertainty is dominated by the 6% uncertainty on the luminosity. The full list of correlated and anti-correlated uncertainties is shown in Table IV.

TABLE III: Summary of systematic shifts of the acceptance ratio $\mathcal{A}_{WZ}/\mathcal{A}_{WW,\mathrm{LJ}}$. In the case of asymmetric uncertainties for the upwards and the downwards shift of a parameter, we chose the larger of the two. Note that the upper grouping contains those systematic uncertainties that are correlated, and the lower grouping includes those anti-correlated between the tagged and the anti-tagged signal regions.

Systematic Uncertainty: Signal Acceptance Ratio	**Base Sel. (%)**	**Tagged Region (%)**	**Anti-Tagged Region (%)**	**Control Region (%)**
Lepton Scale Factor	0.5	0.5	0.5	0.6
Trigger Efficiency	0.2	0.2	0.2	0.2
ISR/FSR	1.8	4.8	5.5	4.0
Helicity Re-Weighting	3.5	3.4	3.6	4.0
Parton Distribution Functions	0.9	0.9	0.9	0.9
Jet Energy Scale		— *Fit Parameter* —		
Total Correlated	3.9	6.2	6.1	5.9
B-Tagging Scale Factor	10.2	5.6	16.1	10.2
Mistag Parameterization	0.6	0.4	1.0	0.6
$\mathcal{B}(t \to Zc)$ versus $\mathcal{B}(t \to Zu)$	0.0	4.5	4.5	0.0
Total Anti-Correlated	10.2	7.2	16.7	10.2

TABLE IV: Summary of systematic uncertainties on the sum of the backgrounds from SM $t\bar{t}$ production and WZ and ZZ diboson production. In the case of asymmetric uncertainties for the upwards and the downwards shift of a parameter, we chose the larger of the two. Note that the upper grouping contains those systematic uncertainties that are correlated, and the lower grouping includes those anti-correlated between the tagged and the anti-tagged signal regions.

Systematic Uncertainty: Small Backgrounds	**Base Sel. (%)**	**Tagged Region (%)**	**Anti-Tagged Region (%)**	**Control Region (%)**
Luminosity	6.0	6.0	6.0	6.0
Lepton Scale Factor	1.3	1.4	1.4	1.3
Trigger Efficiency	0.4	0.4	0.4	0.4
Jet Energy Scale		— *Fit Parameter* —		
Total Correlated	6.2	6.2	6.2	6.2
B-Tagging Scale Factor	0.0	3.1	2.4	0.0
Mistag Parameterization	0.0	0.8	0.7	0.0
Total Anti-Correlated	0.0	3.2	2.5	0.0

B. Shape Uncertainties

We have carefully examined all known sources of shape uncertainties both for the FCNC signal and for the main background from Z+jets events. Jet energy scale (JES) uncertainties show by far the largest overall effect. The mean value of the $\sqrt{\chi^2}$ distribution is shifted by approximately $\pm 5\%$ for a $\pm 1\sigma$ JES shift in the Z+jets background and by approximately $\pm 1\%$ for a $\pm 1\sigma$ JES shift in the FCNC signal. The uncertainty due to JES shifts is taken into account in the template fit via "template morphing."

Smaller but still sizable effects come from the variation of internal parameters in the ALPGEN Monte Carlo generator used to determine the Z+jets background shape. We have simultaneously varied the parameter `qfac`, related to the renormalization and factorization scale, and the parameter `ktfac`, which determines the energy scale at each internal vertex, between 0.5 and 2.0. We observe a variation of up to 17% in the ratio $\mathcal{R}_{\mathrm{sig}}$ of events in the signal regions to events in the control region. As a result, we conservatively assign a 20% constraint on $\mathcal{R}_{\mathrm{sig}}$ in the template fit. We have also verified with pseudo-experiments that we can use JES uncertainties as a "placeholder" for ALPGEN uncertainties. We observe a small bias in the average measured value of $\mathcal{B}(t \to Zq)$, which we take into account by "smearing" all pseudo-experiments accordingly.

TABLE V: Parameters of best fit to the data. The central value of $\mathcal{R}_{\rm sig}$ can be derived from $\sigma_{\mathcal{R}_{\rm sig}}$ and $\sigma_{\rm JES}$: $\mathcal{R}_{\rm sig} = 52.2\%$. Together with the tagging fraction $f_{\rm tag}$, we obtain $Z_{\rm tagged} = 13.5$ and $Z_{\rm anti} = 53.9$ for the number of Z+jets events in the tagged and the anti-tagged signal region.

Fit Parameter	**Value**
Branching Fraction, $\mathcal{B}(t \to Zq)$ (%)	-1.49 ± 1.52
Z+Jets Events in Control Region, $Z_{\rm control}$	129.0 ± 11.1
Shift in Ratio Signal/Control Region, $\sigma_{\mathcal{R}_{\rm sig}}$	-0.61 ± 0.60
Tagging Fraction, $f_{\rm tag}$ (%)	20.0 ± 5.9
Jet Energy Scale Shift, $\sigma_{\rm JES}$	-0.74 ± 0.43

C. Normalization to Top Production Cross Section

We normalize our measurement to the measured $t\bar{t}$ production cross section. As shown in Eq. (3), the number of FCNC events depends on signal yield and the number of expected background events of the $t\bar{t}$ cross section analysis. Hence we add the statistical uncertainty of the signal yield and the total uncertainty of the background for that analysis to the systematic uncertainty of our result. The total normalization uncertainty amounts to 8%.

IV. RESULTS AND CONCLUSIONS

We fit the data with the same fitter we used for the pseudo-experiments to determine the Feldman-Cousins (FC) band. The best fit to the data is shown in Fig. 6 (a). The fitted value of the branching fraction is $\mathcal{B}(t \to Zq) = -1.49\%$. The full list of fit parameters is given in Table V. The p value of this result, i.e. the probability to obtain a measured $\mathcal{B}(t \to Zq)$ of -1.49% or smaller in the absence of a signal, is 26.6%, which corresponds to a $0.62\,\sigma$ downward fluctuation from the expectation. With the help of the FC band we convert the measurement into a 95% C.L. upper limit of $\mathcal{B}(t \to Zq) < 3.7\%$, as depicted in Fig 6 (b). This measurement improves the world's best published limit, 13.7% set by L3 [4], by more than a factor of 3.5 and improves the CDF Run I limit, 33% [3], by an order of magnitude.

In summary, we have presented a search for the flavor-changing neutral current decay of the top quark $t \to Zq$ in events with a Z boson and four or more jets. In $1.9\,\mathrm{fb}^{-1}$ of CDF Run II data we find no evidence for the decay $t \to Zq$ and set the world's best limit on the branching fraction, $\mathcal{B}(t \to Zq) < 3.7\%$ at 95% C.L.

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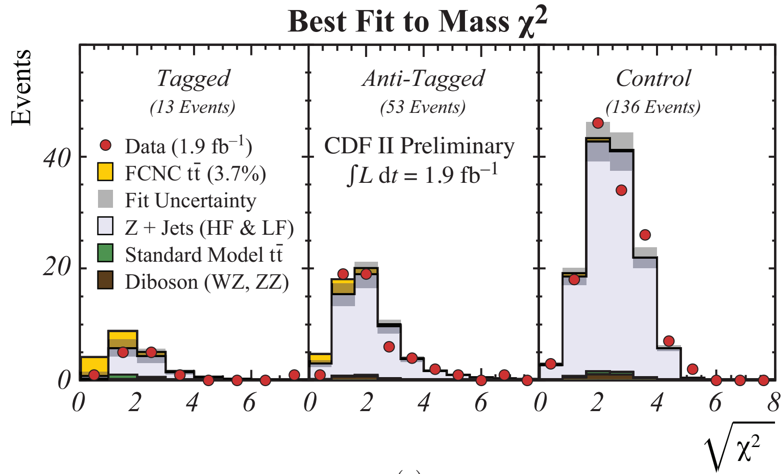
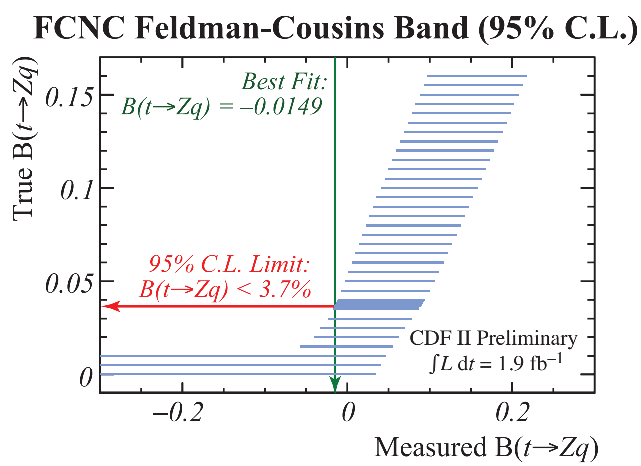


(a)



(b)

FIG. 6: (a) Mass χ^2 distributions for the tagged, anti-tagged, and control regions. We show the data along with the best fit of signal and background templates to the data. Overlaid are the fit uncertainties and the expected signal from top FCNC decays at the observed 95% C.L. upper limit of $\mathcal{B}(t \to Zq) = 3.7\%$. The data is consistent with the background prediction. (b) Feldman-Cousins band with the measured branching fraction $\mathcal{B}(t \to Zq)$.

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[6] CDF uses a right-handed coordinate system such that the positive z-direction aligns with the direction of the proton beam. The other rectangular coordinates x and y are defined pointing outward and upward. We can then work in a polar geometry with $r = \sqrt{x^2 + y^2 + z^2}$ and $\phi = \arctan(y/x)$. From $\theta = \arccos(z/r)$ we define pseudo-rapidity $\eta = -\ln\tan(\theta/2)$ to complete the CDF coordinate system (r, ϕ, η).

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